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Development of New Spectral Amplitude Coding OCDMA Code by Using Polarization Encoding Technique

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Abstract: OCDMA is an optical access technology that has a lot of potential because it can be asynchronously accessed and provides a higher level of security. The authors presented a new DW family code, a flexible double weight (FDW) code, and a novel polarization encoding approach in this paper. The new code is applicable to both odd- and even-weighted codes. The novel polarization encoding approach may be used for numerous wavelengths that overlap. Based on analytic principles, a comparison of two widely used spectrum amplitude-coding SAC-based OCDMA codes, notably modified frequency hopping (MFH), Hadamard, and the double weight (DW) code family. The comparison was based on observing the bit error rate (BER) in each situation. The DW code has a fixed weight of two. The FDW code was introduced to reduce phase-induced intensity noise and multiple access interference (MAI) in transmission networks. FDW codes are versions of the DW code family with weights larger than two. The FDW code outperforms the Hadamard, MFH, DW, modified double weight (MDW), and enhanced double weight (EDW) algorithms. FDW has the capacity to support up to 220 concurrent users. With the new polarization encoding technology, the FDW code can travel up to 60 km at a bit rate of 2.5 Gb/s and 40 km for a 10 Gb/s bit rate.

Keywords: spectral amplitude coding; optical code division multiple access; flexible double weight; modified double weight; enhanced double weight; multiple access interference; bit error rate

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1. Introduction

Optical code division multiple access (OCDMA) is a type of multiplexing technology that is utilized in optical communication systems. It enables the simultaneous transmission of several signals over a single optical fiber, with each signal being identified by a distinct code. OCDMA has the benefit of allowing for high levels of multiplexing, which enables the simultaneous transmission of several signals across a single fiber [1]. This can be helpful in situations when it is necessary to send a lot of data across a long distance, such as in broadband networks. OCDMA systems can also be used in a variety of other applications, including military communications, satellite communication, and biomedical imaging. A spectral amplitude coding (SAC) encoding and decoding technique was developed to eliminate multiple access interference (MAI) within the OCDMA system. Various types of codes were introduced for the SAC technique to counter the problems faced in the previous codes [2]. Each code has its own characteristics, some of which are suitable for local area networks (LAN) and others suitable for metropolitan area networks (MAN) [3,4].

Previous codes, such as Hadamard, modified frequency hoppings (MFH), modified double weight (MDW) and enhanced double weight (EDW) code, have their limitations and drawbacks within OCDMA systems. The previous codes were designed to reduce the crosstalk within OCDMA systems. Hadamard is one of the earliest codes developed in OCDMA systems. To reduce the crosstalk in Hadamard, the code was designed to have a long code length, N, and a small code weight, W [5]. MFH, on the other hand, has larger weight with shorter code length. To design MFH is somewhat difficult and complex compared to the DW family code and Hadamard [6]. There are various types of detection techniques used in the OCDMA system, such as complementary techniques, AND subtraction, single photodiode detector (SPD) [7] and direct detection technique [1,8–10]. In this paper, only AND subtraction and the direction detection technique were used.

Based on the research paper by Rogério N. Nogueira et al. [11], the polarization technique applied differs from the current research. Their technique does not compress the OCDMA code. This is because the polarization is applied for each user, which is not efficient for a higher number of users. By using multiwavelength optical orthogonal (MWOOC) code, the crosstalk between all users has been reduced, but it has longer codewords similar to Hadamard [12]. The longer the codewords, the more susceptible the system will be to noise and interference, as they may be more affected by changes in the optical signal. This can lead to decreased accuracy in decoding the data and potentially lower data rates. In addition, longer codes may require more complex coding and decoding circuitry, which can increase the cost and complexity of the OCDMA system. A research paper by W. Shahroui et al. [13] provides a two-dimensional spatial/polarization encoding approach for an OCDMA system in multi-core fiber. Each user is divided into a separate core. A polarization encoding technique is used to increase the number of users supported and utilize each code word with two users with different polarization [14]. However, the distance is much shorter when using multi-core fiber instead of single-mode fiber [15]. The design is much more complex to apply in single-mode fiber.

The main objective of this research is to develop a new DW family code called flexible double weight (FDW) OCDMA code by using a novel polarization encoding technique to overcome the problem faced in previous systems. FDW code is much easier to design compared to Hadamard, MFH, MDW and EDW code. FDW code has shorter code length, and the number weight can be either odd (EDW) or even (MDW). By using the polarization encoding technique, the code is compressed to support more users with shorter code length. The bit error rate (BER) and signal-to-noise ratio (SNR) determine the quality of data transmission within a specific distance and the number of users. The acceptable number of BER should be 10^{-9}. If the BER is higher than 10^{-9}, the number of bit losses during transmission will be high [16–18]. A new code, flexible double weight (FDW), with a new polarization encoding technique, was designed to support a greater number of users, high throughput, and low power consumption.

2. DW Family Code Construction

DW family code consists of DW, modified double weight (MDW), and enhanced double weight (EDW). Each code characteristic differs in terms of the amount of weight and the code sequence/structure. DW code is the oldest code within the family. MDW code structure is based on DW code with some modification, while EDW code structure is an enhancement of DW and MDW code. The improvement and modification of the code are in terms of the amount of weight it can support (odd or even); the structure of EDW differs from the previous DW family code, and EDW has a shorter code length than the MDW code.

2.1. Modified Double Weight (MDW) Code Construction

Modified double weight (MDW) code is an upgrade of DW code that enables the weight to exceed more than 2. The amount of weight for MDW coding must be an even number. The coding sequence is sustained to 1,2,1. This sequence may preserve the cross-correlation to not greater than 1. The link between the number of users (K) and the code length (N) is indicated in the equation below [3,17].

$$N = 3K + \frac{3}{8}\left[\sin\left(\frac{K\pi}{3}\right)\right]^2 \quad (1)$$

The basic matrix for MDW weight (W) = 4 consists of a 3 × 9 matrix. Therefore, the code sequence for MDW code W = 4 is listed in Table 1.

Table 1. Basic MDW code sequence For W = 4 [17].

K_{th}	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	0	0	0	1	1	0	0	1	1
2	0	1	1	0	0	0	1	1	0
3	1	1	0	1	1	0	0	0	0

The MDW code focuses on enhancing and securing the network. The increase in weight (more than 2) provides better SNR and increases the signal power of the user that is suitable for MAN. The higher the signal power, the larger the area it can cover [17,19].

2.2. Enhanced Double Weight (EDW) Code Construction

EDW code is an enhanced version of the DW code. It is characterized as a low cross-correlation code, where cross-correlation (λ_c) = 1. Unlike DW code, where the code weight is always 2, the weight in EDW can be any odd number greater than 1. EDW has a different sequence and structure than DW and MDW, whereby it contains 2,2,1 rather than 1,2,1. The EDW sequence also preserves the cross-correlation of 1 and enables two overlaps within three columns. The link between the number of users (K) and the code length (N) is given in the equation below [5,20].

$$N = 2K + \frac{4}{3}\left[\sin\left(\frac{K\pi}{3}\right)\right]^2 \frac{8}{3}\left[\sin\left(\frac{(K+1)\pi}{3}\right)\right]^2 + \frac{4}{3}\left[\sin\left(\frac{(K+2)\pi}{3}\right)\right]^2 \quad (2)$$

The basic matrix for EDW weight (W) = 3 consists of a 3 × 6 matrix. Therefore, the basic EDW code sequence for W = 3 is shown in Table 2 [20].

Table 2. Basic EDW code sequence for W = 3 [20].

K_{th}	C_6	C_5	C_4	C_3	C_2	C_1
1	1	0	0	1	1	0
2	1	1	1	0	0	0
3	0	0	1	0	1	1

The sequence differs from a basic code for W = 5 and above due to the new construction method (shifting technique). Table 3 shows the construction of the EDW code for W = 5 [20].

Table 3. Basic EDW code sequence For W = 5 [20].

K_{th}	C_{15}	C_{14}	C_{13}	C_{12}	C_{11}	C_{10}	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	1	0	0	1	1	1	0	0	0	0	1	0	0	0	0
2	1	1	0	0	0	0	1	0	0	1	1	1	0	0	0
3	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0
4	0	0	0	1	0	0	1	1	1	0	0	0	0	1	0
5	0	0	0	0	1	0	0	0	0	1	0	0	1	1	1

3. New Flexible Double Weight (FDW) Code Construction

The FDW code is an improved version of the double weight (DW), MDW, and EDW codes. Unlike the other codes, the amount of weight for FDW is flexible. The amount of weight might be odd (EDW) or even (MDW). The sequence for FDW is nearly identical to that of DW but with significant additions. FDW has a code sequence of 1,2,1,. . .,1n. The basic user code for FDW is fixed at 2, which is unique because the prior code had a separate basic user code for each weight. Tables 4 and 5 present the fundamental code architecture for odd (W = 3) and even (W = 4) FDW.

Table 4. FDW code sequence for W = 3.

K_{th}	C_{10}	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	0	0	0	0	0	0	1	0	1	1
2	0	0	0	0	0	1	0	1	1	0
3	0	1	0	1	1	0	0	0	0	0
4	1	0	1	1	0	0	0	0	0	0

Table 5. FDW code sequence for W = 4.

K_{th}	C_{14}	C_{13}	C_{12}	C_{11}	C_{10}	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	0	0	0	0	0	0	0	0	0	1	1	0	1	1
2	0	0	0	0	0	0	0	1	1	0	0	1	1	0
3	0	0	1	1	0	1	1	0	0	0	0	0	0	0
4	1	1	0	0	1	1	0	0	0	0	0	0	0	0

Based on the code sequence in Tables 4 and 5, the code contains cross-correlation, λ_c equal to one, and high autocorrelation. The relationship between N, K, and W is shown in the universal formula below.

$$N = \left[K + \left[\sin\left(\frac{K\pi}{2}\right)\right]^2\right]W + \left[-\frac{1}{2}K - 1.5 - \left[\cos\left(\frac{W\pi}{2}\right)\right]^2\right]\left[\sin\left(\frac{K\pi}{2}\right)\right]^2 - \frac{1}{2}K\left[\cos\left(\frac{K\pi}{2}\right)\right]^2 \quad (3)$$

The code length may be calculated using Equation (3) by specifying the weight and the number of users. The FDW code structure is based on the DW code structure, which is represented by the letter A. The code is extended as B for pairing chips (even weight, EW) and without pairing chips (odd weight, OW). For OW (W = 3) and EW (W = 4), Equation (4) displays matrix A, and Equation (5) shows matrix B.

$$[A] = \begin{bmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \end{bmatrix} \quad (4)$$

$$[B] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}_{W=3} OR \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix}_{W=4} \quad (5)$$

$$[B] = \begin{bmatrix} 1 & 0 & \cdots & W_B \\ 0 & 1 & \cdots & W_B \end{bmatrix}_{W=n(odd)} OR \begin{bmatrix} 1 & 1 & 0 & 0 & \cdots & W_B \\ 0 & 0 & 1 & 1 & \cdots & W_B \end{bmatrix}_{W=n(even)} \quad (6)$$

To design an FDW, matrix B must have zero cross-correlation properties. For the system to function properly, the cross-correlation properties must be equal to or less than 1. The amount of weight in matrix A, W_A, is set at two, but in matrix B, W_B = $W - 2$. As demonstrated in the equation, the same approach may be extended to a larger amount of weight, such as 5,6,7,. . ., n, respectively. Equations (4)–(6) provide a new code in Equation (7) for W = 3 and Equation (8) for W = 4. A matrix concatenation approach based on the equation below may also be used to create a matrix in Equations (7) and (8).

$$FDW = |AB|$$

$$FDW_{W=3} = \begin{bmatrix} 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \end{bmatrix} \quad (7)$$

$$FDW_{W=4} = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 \end{bmatrix} \quad (8)$$

4. New Polarization Encoding Technique

Based on the fundamental physics of light polarization, a novel encoding system has been developed. Light is a transverse electromagnetic wave with electric and magnetic field vibrations happening at right angles to each other and in any plane at right angles to the direction of motion of the light [21,22]. A novel approach based on the FDW code is used for the same wavelength to create zero cross-correlation properties. Unlike the other DW family codes, FDW is ideal for LAN and can support a higher bit rate. Figure 1 shows the polarization encoding–decoding scheme's block architecture.

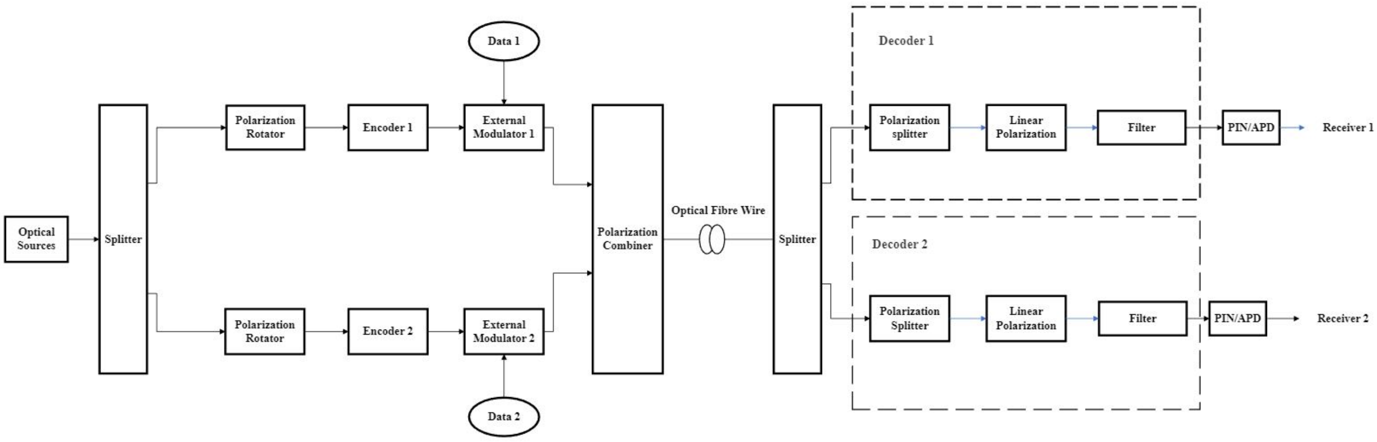

Figure 1. Polarization encoding–decoding scheme block design.

Every two users (basic user, Kb) will be given a specific degree of light rotation to utilize the polarization rotator [21]. This will mean that the wavelengths do not overlap with each other and the original code to be compressed, which is shown in Table 6. The combiner is used to combine all channels into a single-mode optical fiber. The splitter is used to sort all data to a respective receiver. A detection technique is used for decoding the data with the addition of linear polarization for filtering specific degrees of the same wavelength. To determine the performance of the system, an analyzer is added to analyze the number of BERs for each user [22,23].

Table 6. Compression of FDW W = 3 for polarization encoding technique.

Degree of Rotation °	K_{th}	C_5	C_4	C_3	C_2	C_1
0	1	0	1	0	1	1
0	2	1	0	1	1	0
90	3	0	1	0	1	1
90	4	1	0	1	1	0

5. Performance Analysis

In this part, a theoretical analysis of FDW code is compared with previous code, such as Hadamard, modified frequency hopping (MFH), DW code, MDW code, and EDW code. The comparison was particularly made by observing the BER in each case. Each DW family has a unique code that is improved from time to time. A good coding scheme must have high autocorrelation, low cross-correlation (less than 1), and the BERs of less than 10^{-9} for the system to work properly. To compare each DW family code, a few parameters have been fixed, which are shown in Table 7.

Table 7. Typical parameters used in the calculation.

Parameter	Units
Photodetector quantum efficiency (η)	0.6
Operating wavelength (λ_O)	1550 nm
Line width broadband source ($\triangle V$)	3.75 THz
Electrical bandwidth (B)	311 MHz
Receiver load resistor (RL)	1030 Ohm
Receiver noise temperature (T_n)	300 K
Bit Rate	622 Mbps
Fiber Length	10 km

We used a coherent source such as a light emitting diode (LED), and the line width for an LED used in this system is 3.75 THz, which is equivalent to 30 nm. Based on recent studies, the line width of LED can go up to 110 nm, which is equivalent to 13.7 THz for the center wavelength of 1550 nm [24]. To calculate the line width of the LED, the center wavelength is set to 1550 nm. The calculation of the line width requires the bandwidth wavelength (λ), center wavelength (λ_O) and speed of light (c). The center wavelength determines the line width of an LED, which is based on the equation below,

$$Linewidth = \frac{c}{\lambda_O - \frac{\lambda}{2}} - \frac{c}{\lambda_O + \frac{\lambda}{2}} \quad (9)$$

5.1. Theoretical Analysis

FDW code system analysis is assumed to have zero cross-correlation properties due to a new encoding technique (polarization technique). These properties use a direct detection technique for the decoding technique. In a theoretical analysis for the proposed system, a noise must be considered in the calculation, such as PIIN (phase-induced intensity noise, I_{PIIN}), shot noise (I_{SHOT}), and thermal noise (I_{Th}) [25–27]. Using direct detection technique, PIIN noise is eliminated in the calculation due to zero cross-correlation properties. Let $C_K(i)$ denote the ith element of the K_{th} FDW code sequence. The properties of FDW code can be expressed as:

$$\sum_{1=K}^{N} C_K(i)C_l(i) = \begin{cases} W, & \text{for } K = l \\ 0, & \text{else.} \end{cases} \quad (10)$$

The power spectral density (PSD) of the received optical signal can be written as:

$$r(v) = \frac{P_{sr}}{\Delta V} \sum_{k=1}^{K} d_K \sum_{i=1}^{L} C_K(i) \left\{ u\left[V - V_0 - \frac{\Delta V}{2N}(-N + 2i - 2) - u\left[v - v_o - \frac{\Delta V}{2N}(-N + 2i) \right] \right] \right\} \quad (11)$$

the unit step function $u(v)$ can be expressed as:

$$u(v) = \begin{cases} 1, & v \geq 0 \\ 0, & v < 0. \end{cases} \quad (12)$$

From Equation (11), the power spectral density at the photodetector is:

$$G(v) = \frac{P_{sr}}{\Delta V} \sum_{k=1}^{K} d_K \sum_{i=1}^{L} C_K(i)C_l(i) \left\{ u\left[V - V_0 - \frac{\Delta V}{2N}(-N + 2i - 2) - u\left[V - V_o - \frac{\Delta V}{2N}(-N + 2i) \right] \right] \right\} \quad (13)$$

the equation can be simplified much further, let

$$
\begin{aligned}
M &= \left\{ u\left[V - V_0 - \frac{\Delta V}{2N}(-N+2i-2) - u\left[V - V_o - \frac{\Delta V}{2N}(-N+2i) \right] \right] \right\} \\
&= \left\{ u\left[V - V_0 - \frac{\Delta V}{2N}(-N+2i-2) - V + V_o + \frac{\Delta V}{2N}(-N+2i) \right] \right\} \\
&= \left\{ u\left[-\frac{\Delta V}{2N}(-N+2i-2) + \frac{\Delta V}{2N}(-N+2i) \right] \right\} \\
&= \left\{ u\left[\frac{\Delta V}{2} - \frac{\Delta V}{N}i + \frac{\Delta V}{N} - \frac{\Delta V}{2} + \frac{\Delta V}{N}i \right] \right\} \\
M &= \left\{ u\left[\frac{\Delta V}{N} \right] \right\}
\end{aligned} \tag{14}
$$

applying Equation (13) with Equation (14) to obtain the equation below:

$$
\begin{aligned}
G(v) &= \frac{P_{sr}}{\Delta V} \sum_{k=1}^{K} d_K \sum_{i=1}^{L} C_K(i) C_l(i) [M] \\
&= \frac{P_{sr}}{\Delta V} \sum_{k=1}^{K} d_K \sum_{i=1}^{L} C_K(i) C_l(i) \left\{ u\left[\frac{\Delta V}{N} \right] \right\}
\end{aligned} \tag{15}
$$

where P_{sr} is the effective power of a broadband source at the receiver, K is the number of active users, N is the code length of the FDW code and d_k is the data bit of the K_{th} user, which is "1" or "0". The photocurrent of the receiver, I_p, is defined by [28]:

$$
I_p = \Re \int_0^\infty G(v) dV \tag{16}
$$

where $\Re$ is the responsivity of the photodetector, and $\int_0^\infty G(v) dV dV$ is the total power of the photodiode [26,27]. Integrating the PSD in Equations (11) and (16), the obtained result is:

$$
\int_0^\infty G(v) dV = \int_0^\infty \left[\frac{P_{sr}}{\Delta V} \sum_{k=1}^{K} d_K \sum_{i=1}^{L} C_K(i) C_l(i) \left\{ u\left[\frac{\Delta V}{N} \right] \right\} \right] dV \tag{17}
$$

When all users are transmitting bit "1":

$$
\sum_{k=1}^{K} d_K = W \tag{18}
$$

the photocurrent can be expressed as:

$$
I_p = \Re \left[\frac{P_{sr} W}{N} \right] \tag{19}
$$

the variance of photocurrent can be expressed by:

$$
\langle i^2 \rangle = 2eBI_p + \frac{4K_b T_n B}{R_L} \tag{20}
$$

by using Equations (19) and (20), an SNR for direct detection technique can be derived as follows [26]:

$$
SNR = \frac{(I_p)^2}{\langle I^2 \rangle} \tag{21}
$$

$$SNR = \frac{\frac{\Re^2 P_{sr}^2 W^2}{N^2}}{\frac{2eB\Re P_{sr} W}{N} + \frac{4K_b T_n B}{R_L}} \tag{22}$$

Thus, the BER is obtained by [26]:

$$BER = \frac{1}{2} erfc\sqrt{\frac{SNR}{8}} \tag{23}$$

Based on Equations (22) and (23), respectively, the results of BER are shown in Figure 2. Note that Figure 2 shows a significantly better performance FDW can support more than 220 simultaneous users compared to EDW, which can support no more than 80 simultaneous users before the system starts to degrade. This is due to the superior code properties of the FDW code, such as cross-correlation, which is always equal to one. By using a polarization encoding technique, the code can support much more users, as shown in the analysis. Hadamard and MFH, on the other hand, can support no more than 30 simultaneous users. Hadamard was designed to have a long code length, N and a small code weight, W. This is because the temporal overlap between pulses from different users at the intensity correlator output is much smaller. These previous codes have much higher bit error rate (BER), and the number of coactive users is also limited. Hadamard code is not an efficient code because as the number of users increases, the cross-correlation will also increase. MFH has an ideal cross-correlation, but the code structure is complicated to design. In order for MFH to increase the performance in Figure 2, the amount of weight, W, and the value of Q must be increased. The design will become much more complex as the amount of weight and Q increases [29]. The number of code sequences supported by MFH is determined by the value of the prime integer Q. The relationship between the maximum number of users and the value of the prime number Q for the MFH code sequence is given by $K = Q^2$. The prime number Q can have any value, such as 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53,. . ., $Q_{PrimeNumber}$. For $Q = 7$, the maximum number of users that MFH can accommodate is 49. However, based on theoretical calculations (refer to Figure 2), the maximum number of users can only support up to 30 users with a BER of 10^{-9}, leaving 19 codes unused and making the code less efficient. However, the FDW code family is clearly more efficient because the sequence can be generated precisely according to the number of users.

In addition, the performance of FDW is also determined based on BER vs. received power, Psr(dBm), as shown in Figure 3. Note that the Hadamard code has a slightly better BER at −25 dBm than FDW code, but FDW code has a much better BER at −20 dBm than Hadamard, MFH, MDW and EDW code. To obtain a clear explanation, the graph signal and noise power of the OCDMA code were plotted in Figure 4. The noise power for Hadamard and MFH is higher than FDW code when the Psr reaches −20 dBm and above. FDW signal power is in between Hadamard and MFH, in which Hadamard has the highest signal power. However, due to the noise power increasing exponentially, the overall performance of Hadamard and MFH systems drop significantly. FDW has the lowest noise power, which makes the system much more stable than previous systems. At 10 km distance of optical fiber, an optical signal-to-noise ratio (OSNR) at −20 dBm Psr for the FDW system is 29.98 dB (OSNR (dB) = Signal Power − Noise Power). Table 8 shows a comparison of various types of OCDMA code performance. FDW has the largest OSNR value compared with other codes. Higher OSNR means better signal quality with less noise interference. This is important to ensure the signal can travel a long distance with low degradation. The noise power for Hadamard and MFH is much higher than FDW and MDW code, which causes the OSNR to drop at −15 dBm and above. The DW family code has proved its superior performance by suppressing the shot noise. The signal power can be increased by increasing the amount of weight of OCDMA codes.

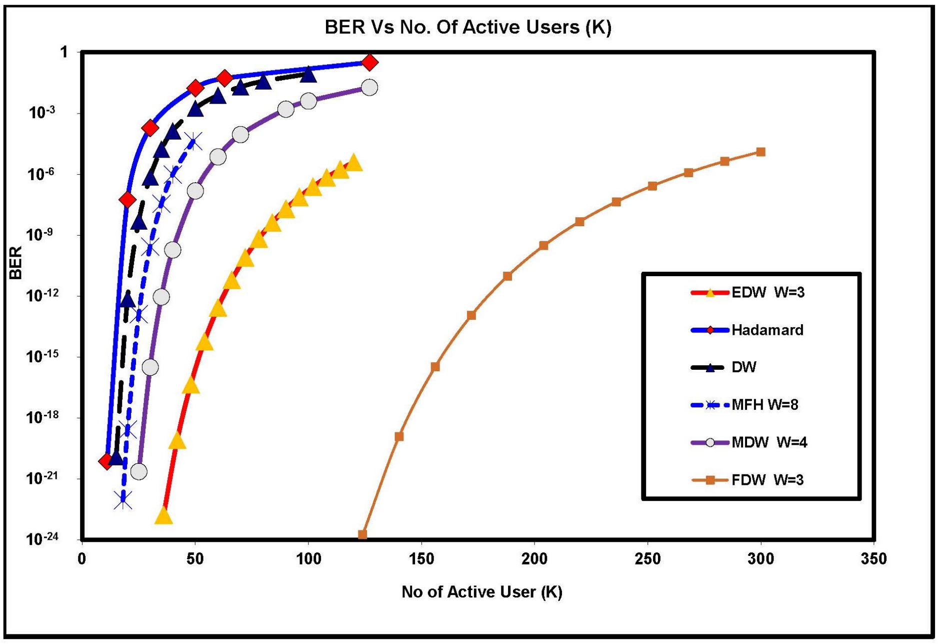

Figure 2. Performance of OCDMA code BER versus the number of users (K).

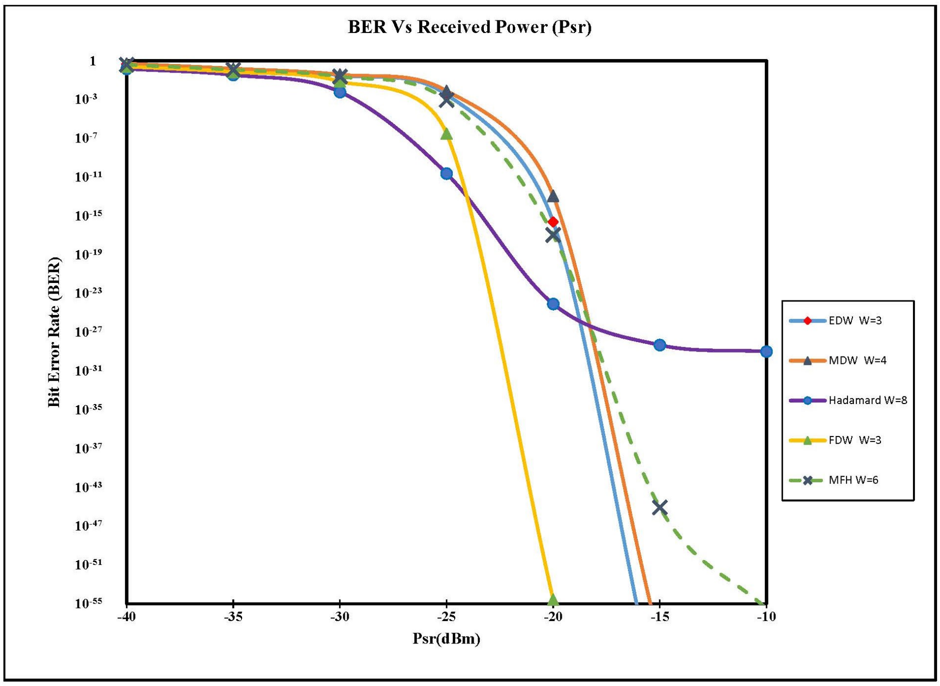

Figure 3. Performance of OCDMA code BER versus received power, Psr (dBm).

Table 8. Comparison of OCDMA code based on code length and OSNR.

OCDMA Code	No of Users	No of Weight	Code Length, N	OSNR (dB)
Hadamard	9	8	16	26.21
MFH	9	6	31	24.6
MDW	9	4	27	23.33
EDW	9	3	18	24.21
FDW	9	3	12	29.89

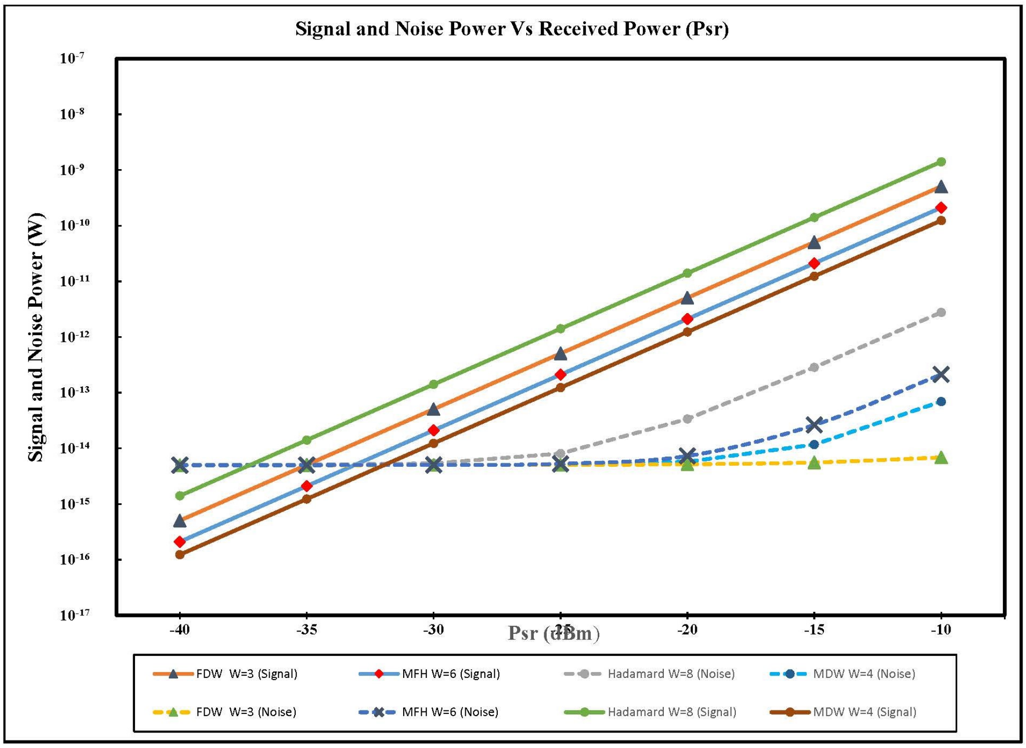

Figure 4. Performance of OCDMA code signal and noise power (W) versus received power, Psr (dBm).

5.2. Simulation Analysis

The performance of the FDW code was simulated using OptiSystem version 15. The test was carried out with a bit rate of 2.5 Gb/s for a 40–60 km distance with single-mode optical fiber. The spectral width for each chip is set to 0.8 nm. The dark current value is 1 nA, and the thermal noise coefficient is 1×10^{-22} W/Hz for each photodetector. The performance of the FDW code is based on the BER obtained for each receiver. Figures A1–A3 in the Appendix A section show eye pattern results for 40–60 km optical fiber length.

Based on the simulation results, the eye pattern result degrades as the distance increases. The system can go up to 60+ km before the signal is distorted. The BER for 60 km optical fiber distance is 2.11951×10^{-11}, which is lower than 10^{-9}. The acceptable amount for BER is less than or equal to 10^{-9}.

To establish the reliability of the FDW system, tests were conducted based on the effect of different bit rates with distance. Figure 5 shows the graph of BER vs. distance for different bit rates applied on the FDW system. The graph provides a clear view on FDW system performance. On 10 Gb/s, the system can go up to 40 km, which has the BER 1.15×10^{-10}. 1 Gb/s bit rate able to travel 70 km, while the 5 Gb/s bit rate is capable of reaching up to 50 km. Based on this observation, FDW can support high data rates and can cover long-distance applications such as a metropolitan area network (MAN).

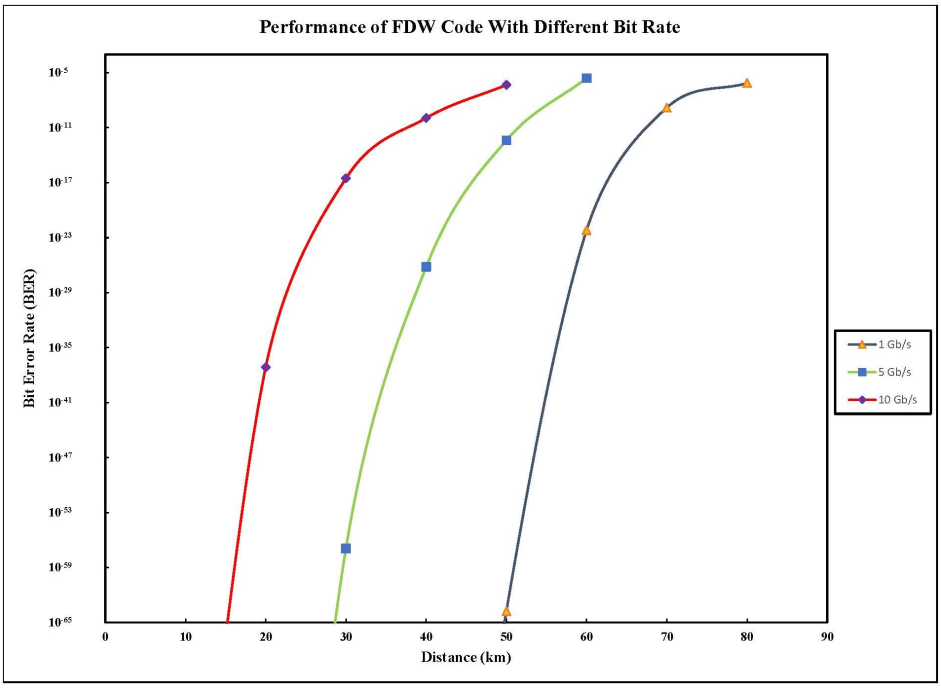

Figure 5. Performance of FDW code with different bit rate.

6. Conclusions

In OCDMA systems, each user is assigned a sequence code that acts as their address. An OCDMA user modulates its code (or address) with each data bit and asynchronously initiates transmission. Hence, this affects its spectrum appearance in a way recognized only by the chosen receiver. The first OCDMA code is the Hadamard code, which experienced various hurdles during the field test. The performance of the OCDMA system degrades when the number of simultaneous users grows. This is connected to MAI, which results from the incomplete orthogonal of the employed signature codes. The DW family of codes was meant to relieve the difficulties discovered in the preceding codes, such as the number of simultaneous users supported and MAI. A good functional code must have low cross-correlation and strong autocorrelation for the system to have improved performance. FDW codes are the newest DW code family variations with variable weights bigger than two. The new polarization encoding technique has provided a better solution for achieving zero cross-correlation properties. The equation for the FDW code family was used for SNR and BER calculations to compare the performance of the code. FDW code with a polarization encoding technique has substantially greater performance compared to Hadamard, MFH, DW, MDW, and EDW codes. FDW can accommodate more than 220 simultaneous users. In the simulation, FDW code with the new polarization encoding technique can go up to 60 km distance for a 2.5 Gb/s bit rate and 40 km for a 10 Gb/s bit rate.

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Abbreviations

The following abbreviations are used in this manuscript:

SAC	Spectral Amplitude Coding
OCDMA	Optical Code Division Multiple Access
DW	Double Weight
MDW	Modified Double Weight
MWOOC	Multiwavelength Optical Orthogonal Code
EDW	Enhanced Double Weight
ZCC	Zero Cross-Correlation
FDW	Flexible Double Weight
OW	Odd Weight
EW	Even Weight
LAN	Local Area Network
MAN	Metropolitan Area Network
MFH	Modified Frequency Hopping
MAI	Multiple Access Interference
BER	Bit Error Rate
PIIN	Phase-Induced Intensity Noise
OSNR	Optical Signal-To-Noise Ratio
SNR	Signal-To-Noise Ratio
PSD	Power Spectral Density
SPD	Single Photodiode Detector

Appendix A

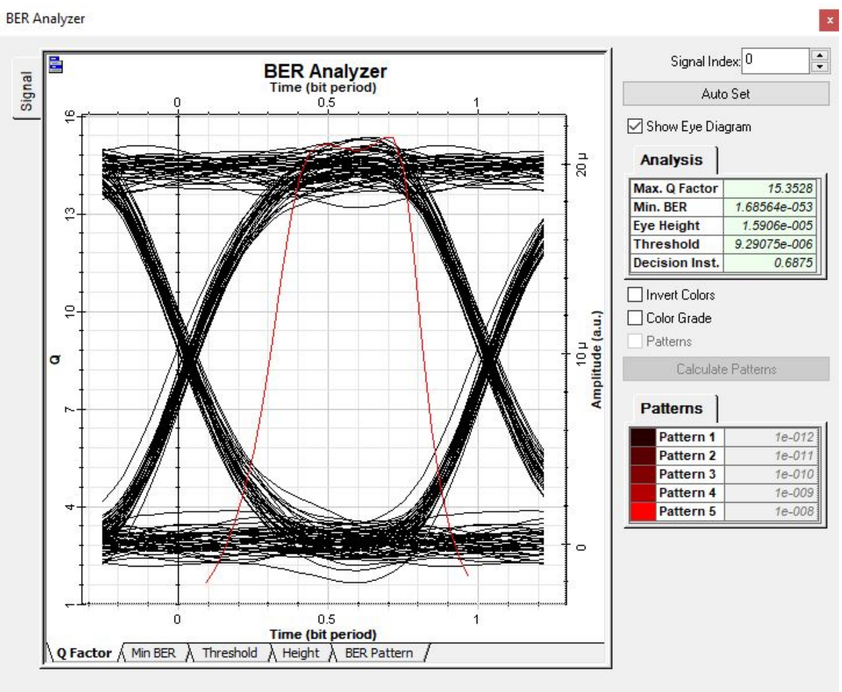

Figure A1. Receiver 1 eye pattern for 40 km distance.

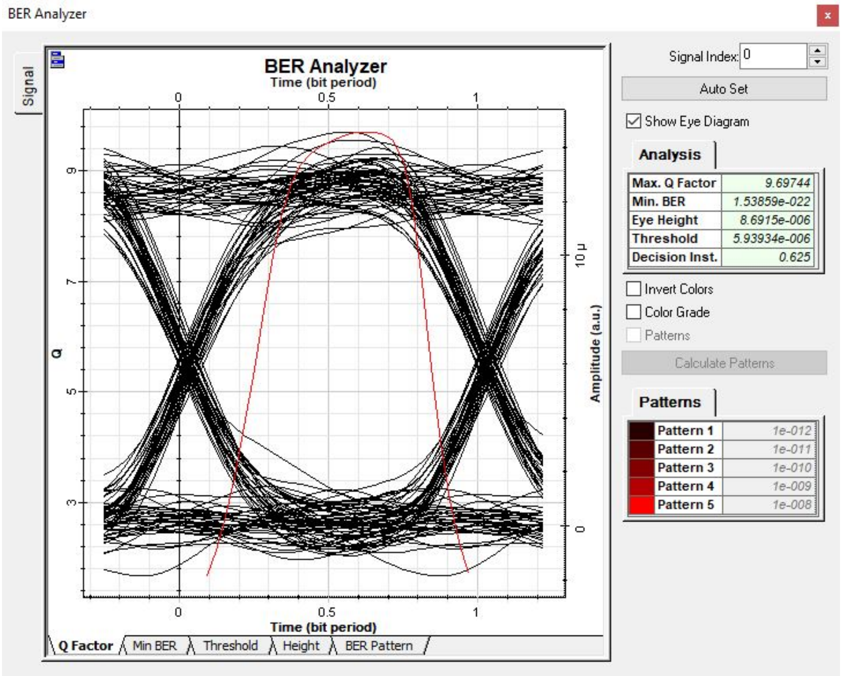

Figure A2. Receiver 1 eye pattern for 50 km distance.

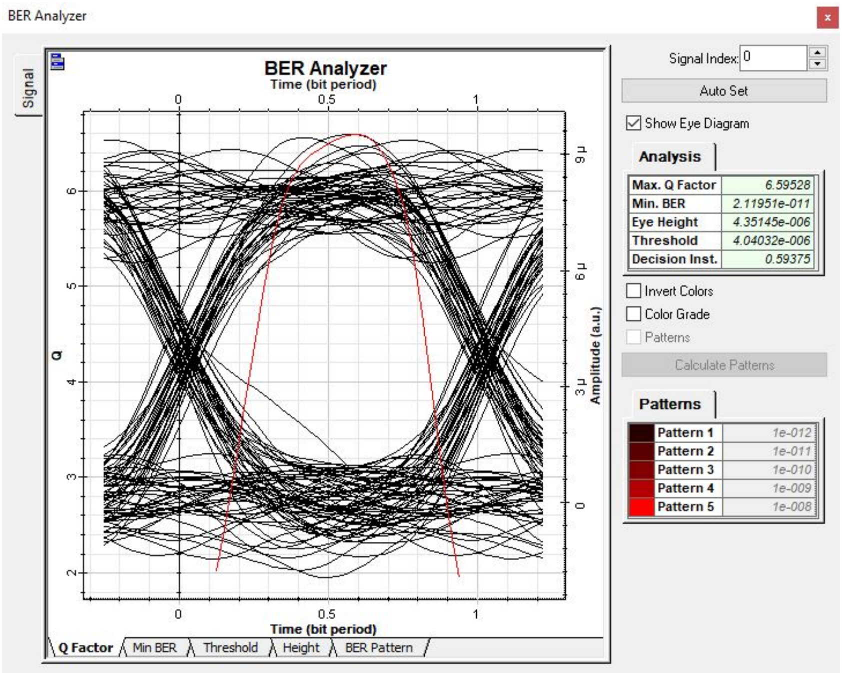

Figure A3. Receiver 1 eye pattern for 60 km distance.

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